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Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings

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Keywords

sustainable building; life cycle assessment; embodied energy; embodied GHG emissions; methodological choices; EN15978 standard

Abstract

The importance of embodied energy and embodied greenhouse gas emissions (EEG) from buildings is gaining increased interest within building sector initiatives and on a regulatory level. In spite of recent harmonisation efforts, reported results of EEG from building case studies display large variations in numerical results due to variations in the chosen indicators, data sources and both temporal and physical boundaries. The aim of this paper is to add value to existing EEG research knowledge by systematically explaining and analysing the methodological implications of the quantitative results obtained, thus providing a framework for reinterpretation and more effective comparison. The collection of over 80 international case studies developed within the International Energy Agency's EBC Annex 57 research programme is used as the quantitative foundation to present a comprehensive analysis of the multiple interacting methodological parameters. The analysis of methodological parameters is structured by the stepwise methodological choices made in the building EEG assessment practice. Each of six assessment process steps involves one or more methodological choices relevant to the EEG results, and the

combination potentials between these many parameters signifies a multitude of ways in which the outcome of EEG studies are affected.

1 Introduction

Buildings are responsible for more than 40 percent of global energy used, and as much as one third of global greenhouse gas emissions [1]. The environmental impacts from buildings are of operational as well as embodied character, where embodied energy and greenhouse gas emissions (EEG) from buildings concern exchanges with the environment from processes that take place in relation to the life cycle of the building materials, for example the production processes of cement clinker which requires heating energy and which emits CO2 from energy conversion as well as chemical processes. It is increasingly recognized that EEG can constitute more than half of the total life cycle impacts from new buildings and is thus a key element to address when working towards a more sustainable building sector [2].

On a regulatory level, focus from international, as well as, from regional political bodies may act as a driver for national development of measures to reduce EEG from buildings [1][3]. Preliminary steps towards regulatory guidelines and/or requirements are thus seen in several countries [4][5][6][7]. This regulatory attention follows an already existing focus within the building sector itself, where voluntary initiatives include EEG considerations as part of holistic evaluations of the sustainability of buildings, e.g. as practiced in various certification schemes.

Furthermore, methodological improvements have been made in developing and harmonising the life cycle assessment (LCA) method by which the EEG is quantified. Building and construction related standards include the international standard ISO 21931-1:2010, which specifies the framework for methods of assessment of the environmental performance of construction works, and the European standard EN 15978:2011 which specifies a calculation method for assessing the environmental performance of a building. In parallel with the standardisation development, a number of international research projects have focused on LCA and EEG in the building sector. These activities are carried out e.g. in a European context [8][9][10], but also in an international context through e.g. the International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC). Relevant IEA-EBC research work include, most recently, the Annex 57 on EEG in buildings (2011-2016)[11].

In spite of all the attention towards EEG and the efforts in harmonising a methodological approach, research has pointed to the lack of consistency in the ways building LCAs are carried out, both in terms of system boundary definition and in terms of the indicators and the background data used for calculating the embodied impacts [12][13][14][15]. Thus, reported EEG of buildings display large variations in numerical results as well as inconsistent and insufficient reporting formats [16].

Knowledge on how to reduce EEG through certain design strategies can be drawn from the experiences and analyses of the, so far, mostly individual case studies. This can guide building designers, as well as, policy developers targeting reductions of EEG. However, it is highly important that the methodological reasons for differences in EEG results is fully understood. Conversely, incorrect conclusions may be drawn and used for creating and validating EEG-reducing design strategies, although these may not actually have the desired reduction potential. Existing literature, mainly in reviews, has described methodological parameters of importance, further explained in section 1.2. However, the parameters treated in existing literature appear randomly sought out and thus do not provide a systematic overview that links directly to the EEG assessment practice.

The aim of this paper is to add value to existing EEG research knowledge by systematically explaining and analysing the methodological implications on the quantitative results obtained, thus providing a framework for reinterpretation, more effective comparison and understanding of reduction potentials in quantitative terms.

The systematic approach of this paper includes the consideration of the already scientifically addressed methodological parameters, which are presented in the literature review in section 1.2. The method section 2 introduces a structured framework for analysis based on the practical assessment process of the EN 15978 standard. Furthermore, section 2 describes the collection of over 80 building case studies from the IEA-EBC Annex 57 project, an international collection of EEG assessments that are reported in a consistent and organised manner and thus provides detailed and illustrative examples of methodological implications. The results and discussion section 3 uses the quantitative as well as the qualitative properties of the Annex 57 case studies to analyse and empirically validate the methodological parameters that affect the outcome of EEG studies, and the section presents a comprehensive and structured overview of these.

1.1 Defining the concept of EEG

Life cycle environmental impacts from and resource uses in buildings are often categorised as being operational or embodied. Operational energy is intuitively understood and defined as being the energy needed to maintain comfortable conditions in the building through processes such as heating, ventilation, air conditioning, hot water supply, lighting or operational waste management[17][18][19]. The emissions of energy-related pollutants from the building operation, e.g. greenhouse gasses such as CO_2, can likewise be regarded as operational impacts [20].In contrast to the impacts related to operational energy use, embodied energy use and greenhouse gas emissions are understood as material-related impacts, i.e. the impacts stemming from the processes that take place in relation to the life cycle of the building materials [21][2][22].

EEG may be sub-classified to reflect the part of the building life cycle in which they occur. Typically, this way of classifying embodied impacts is divided into initial and recurring embodied impacts. Initial impacts signify those related to the processes occurring up to the point in time where the building is taken into use, and recurring impacts signify the material-related processes occurring throughout the building's use stage, e.g. maintenance and replacements [17][2] . Added to the initial and recurring embodied impacts are the impacts which occur after the end of the building's service life. These are commonly termed demolition impacts [23][17][2], although they also cover waste treatment, transport and disposal processes as well as impacts from the demolition processes. Some studies suggest the benefits and loads from recycling potentials as an additional life cycle stage of importance to the life cycle impacts of a building [24][25][26]. The integration of this life cycle stage as an element of the embodied impacts however, depends on the modelling approaches towards recycling used in the life cycle inventory of a particular study [27][28]. Consequently, results from this life cycle stage are recommended or required as reported separately from the results of the remaining life cycle stages [26][29][30].

EEG studies of buildings display wide variations in terms of the life cycle stages included [31][32]. It can thus be useful to distinguish between different types of system boundaries used in studies of EEG in buildings, for instance by a cradle to gate perspective where impacts are accounted from processes only to the point in time where the building materials are ready to leave the gate of the manufacturing facilities. The EN 15978 standard, published in 2012, presents a modular structure for defining five main life cycle stages; production, construction, use, end of life (EoL), and finally the benefits and loads beyond the system boundary. This modular structure can be further categorised to reflect impacts at the different types of system boundary definitions as illustrated in Figure 1.

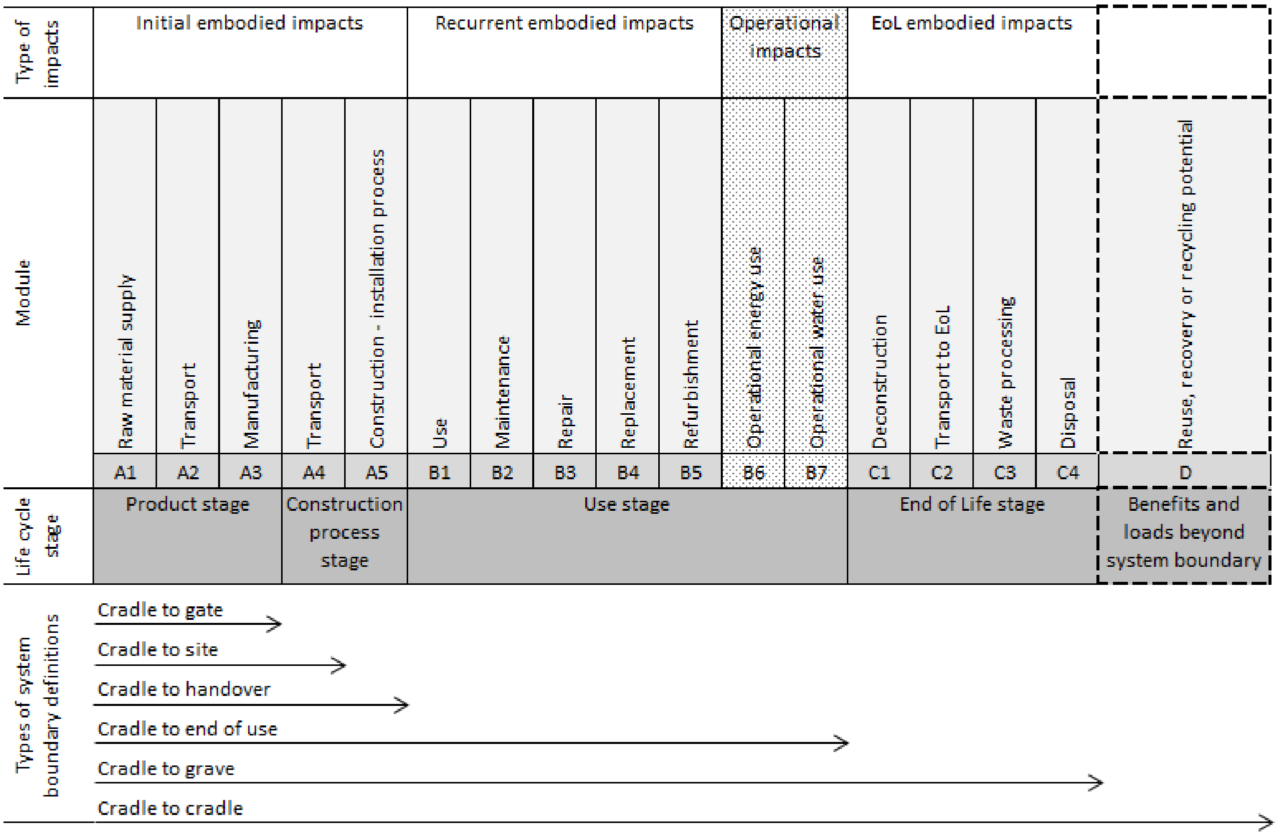

Figure 1. System boundaries definitions in relation to the life cycle stages of a building [30][29][18]

1.2 Ranges of and sources for EEG variations

1.2.1 Variations of EEG results

Embodied energy use of buildings is mainly addressed in literature within the context of life cycle energy evaluations, hence including the operational energy use in the building's use stage. A review by Sartori and Hestnes [33] thus found the embodied energy's share to range between 2 and 46 % of the total life cycle energy. Ramesh et al. [17] reviewed many of the same case studies as well as newer studies and found a numerical range of embodied energy use between 7 and 143 kWh/m^2/year. Reviews focusing on the initial embodied energy use of buildings reports numbers in ranges between 1,500 and 19,400 MJ/m^2 [34][21][35][36]. Hence, horizontal comparisons of EE studies show ranges spanning up to an approximate factor 20.

Studies reporting ranges of EG in buildings are fewer than EE studies, but still expresses variations in the reported ranges of results, i.e. in Hammond and Jones [21] and Hacker et al. [37] where the initial EG is reported to vary between 228 and 606 kg CO_2-eq/m^2, hence an almost three-fold difference.

As indicated from these previous reviews, the variations in results of EE and EG are profound. Part of the variations can be explained by variations in building design, materials used, building function, etc., that is, physical properties of the buildings, their location and use. One example is the study by Passer et al. [38] comparing variations of building material solutions for a single family house presents ranges of 4.5 - 7 CO_2-eq/m^2/year and 17 - 25 kWh/m^2/year for the initial embodied impacts. These results are within a range with maximum variations of approximately 70 % or a factor of 0.7 and thus only explains part of the 20- and three-fold differences. Ramesh et al [17] review results distributed on building types and show practically the same large variations within the categories of offices and residential buildings, 30-140 kWh/m2/year and 7-143 kWh/m2/year respectively, hence pointing to building type as an inferior determinant of the results when comparing different studies.

Thus, differences in building designs may account for some of the variations of EE and EG results presented in literature, but the better part of the variations seem determined by the study design i.e. the methodological choices made for the assessment. Sources for these variations are randomly described in various literature sources which mainly focus on the indicator definitions, the background data, the modelling approach, the system boundaries and the scenario definitions [18][12][39][2][17][40], which are all explained in more detail in the following sections 1.2.2-1.2.6.

1.2.2 Definitions of EE and EG indicators

Embodied energy (EE) is most appropriately accounted for in its primary form, i.e. at the energy source level before conversion, as opposed to the end-use energy at consumer [33][18]. The indicator used to express the primary energy use (PE) is also referred to as cumulative energy demand (CED), a term that expresses the accumulative nature of the indicator in which energy uses from different processes of the life cycle stage are successively added. However, as described by Frischknecht et al. [41], there is no harmonised definition of the indicator. Hence, the reported use of primary energy in a study may rely on choices of upper or lower heating values in chemical energy resources, the energy content in uranium and the determination of energy resource inputs of renewable energies. Furthermore, the feedstock energy, e.g. the retained energy in petrochemical-based plastics and rubbers, is rarely reported as being included or excluded of the primary energy indicator of building case studies [29][18][42].

There is also a range of varying definitions and considerations for the embodied greenhouse gas emissions (EG). EG is closely related to energy since fossil or bio-based energy generation releases the greenhouse gas (GHG) CO_2, and thus the CO_2 emissions related to energy use are proportional for a given fuel mix [2]. However, there are two main aspects which mean that EG is not directly proportional to EE. Firstly, EG includes CO_2 as well as other greenhouse gases, although the actual types of included greenhouse gasses may differ according to the chosen scope which can be e.g. the GHGs from the Kyoto protocol or the GHGs from the latest IPCC report. Fluorocarbon gasses as regulated by the Montreal Protocol may also be included [43]. In relation to defining the types of GHGs are also the considerations on the characterisation factors used to express all included GHGs in CO_2-equivalents and the temporal scope in which the emissions and environmental loads are considered [13].

Secondly, EG also includes emissions of greenhouse gases from chemical and physical processes during the life cycle of the building materials, e.g. CO_2 from the cement clinker process or leakage of fluorocarbon gasses from air condition appliances [13]. Correspondingly, building materials of biological origin, e.g. wood products, may sequester and temporarily store CO_2. There are different approaches for accounting for biogenic carbon storage in LCA, and these can lead to large differences in the final EG results [44] [45].

1.2.3 Representativeness of background data

Representativeness of background data concerns the fundamental match between the processes included in the building model and the background data which describes the environmental impacts of the process. The ISO 14044:2006 data quality requirements addresses the importance of representative data at three levels of coverage; time-related, geographical and technological coverage [46]. In relation to EEG, these aspects are also identified as contributing to the difference in results found in several studies of applied building LCA [12], in the comparison of different generic databases [47][40] and in the comparisons of generic databases and environmental product declarations (EPDs) [48][49][50].However, clarification and harmonisation is still needed, for example on aspects of system boundaries, allocation practices and service life of products and buildings [51].

1.2.4 Modelling approaches

Two distinct modelling approaches are used in LCA practice; the input-output based and the process based. Hybrid models based on the two are also used. The two approaches possess different strengths and limitations in terms of completeness and accuracy [15][18]. These are reflected in reported EEG results where input-output and hybrid based models tend to produce results in higher ranges [52].

1.2.5 System boundaries

The difference in chosen system boundaries is pinpointed in several review studies as one of the foremost reasons for incomparability between EEG studies of buildings [18][32][17][31]. A progressive development towards a harmonised approach in reporting the building's life cycle stages has taken place following the international and European standardisation efforts in this field. However, the aspect of system boundaries is not limited to clarifying the building's life cycle stages. Dixit et al. [39] describes how the system boundaries may in reality be characterised as consisting of three distinct dimensions that are all spanning upstream and downstream processes;

1. One dimension covers the life cycle stages, e.g. extraction of raw materials or transport of materials to building site. Some research highlights the need for simplification of the included life cycle stages in order to limit the amount of calculation work and thus to make the LCA and EEG evaluations implemented and used by architects and engineers as part of the building design process [10] [53][54]. Other research points to the relevance of some life cycle stages that are often omitted from studies, e.g. the construction stage, or the transport to site [55][56] and emphasises the additional relevance by the timing of GHG emissions from the before-use stages [57]. Naturally, the difference in included life cycle stages leads to difference in EEG results. However, as noted by for instance Optis et al. [16], the simplifications of life cycle stages follow the goal and scope of the study in question.
2. A second dimension covers the width of included inputs and outputs for each life cycle stage, e.g. the resources used as input for the extraction of raw materials. This affects results at two levels; at inventory level for building/building component, where e.g. omitting fixtures and fittings in some cases may be significant [56]. Secondly, at inventory level for materials found in the applied building material databases, where there may be differences in the number of substances and emissions accounted for [58].
3. A third dimension that covers the physical entity being assessed, e.g. building component level or building with site. Because this dimension indicates the scope of the study, this naturally changes across different studies.

1.2.6 Scenario definitions

Scenario related differences found in literature focus on building level scenarios as well as material level scenarios. For building level scenarios, studies have stressed the influence on EEG results of the building's estimated service life, which in turn influences the total amount of materials used for replacements etc. Aktas and Bilec [59] refer a range of LCA studies in which the building service lives are explicitly stated as being arbitrarily set, hence underlining the lack of a viable method to estimate a building's life time. Several building case studies have investigated predetermined sets of potential service lives in order to address the sensitivity of the modelled results [60][61] or specifically focusing on the impact on results of service life variations [62][63]. Some studies also present methodologies for addressing the combined effects of variations in the building's service life and variations in the service life of materials [59][64].

Apart from the service life aspect, scenario analyses on building scale furthermore include approaches to evaluating the significance of scenarios for single life cycle stages, e.g. scenarios for construction [65][66]. At building material level, investigations of scenario choices include those of maintenance frequencies [67], transport [68] and EoL treatment options [25] [69][70].

2 Method

2.1 The Annex 57 case study collection

The IEA-EBC Annex 57 research work was organised into four subtasks, each focused on different aspects of EEG in buildings[11]. Subtask 4 was responsible for identifying strategies for the reduction of EEG. In order to do so, the subtask 4 work group collected more than 80 building case studies from the multi-national project partners, chosen to be representative of the information on EEG currently available both in emerging academic publications and within different national contexts [71].

The purpose of the Annex 57 case study collection was to produce a body of different detailed studies, carried out in different countries and for different purposes, for which the relevant data was easily accessible and identifiable. The case studies were subjected to four sequential analytical perspectives: the impacts of methodological issues on the EEG results obtained (the focus of this paper); comparing the impacts from different life cycle stages, materials and components; evaluating design and construction strategies which can be used to reduce EEG from buildings; and considering the influence of geo-political, organisational and cultural context on the measurement and reduction of EEG [72].

The initial preparatory work was the development of a systematic template, designed to allow the widest variety of studies – including qualitative studies – whilst encouraging transparency and completeness of quantitative data [73]. This approach enabled the comparable interpretation of the high number of complex and detailed case studies by multiple authors. Case studies were submitted using the prepared template, and raw data or public academic literature and reports were also made available and were referenced within each case study description. The case studies as transcribed to the templates therefore all report a number of specific characteristics in a consistent manner; the databases used for calculations, the reference study period, the included life cycle stages of the assessment (based on the modular framework of the EN 15978 standard) and the building type and location.

In spite of the template format, reported EEG results of the case study buildings were still given in a wide variation of formats, for example from the total EG over the full building life cycle per m^2 floor area per year (kg CO_2-eq/m^2/year), to only the EG from the building materials production stage (cradle to gate). For further use in the analysis, these diversely reported results have been adjusted for the reported floor area, reference study period and reported life cycle stages.

The case study collection spans a wide range of EEG case studies carried out for different purposes and is valuable in the sense that it also includes examples of how building LCA is applied in practice. Hence, the studies are not only aimed for international research and scientific publications but also contain evaluations of EEG carried out as part of certification schemes, national research projects and academic theses.

2.2 A structure for identification of significant parameters

In order to identify and discuss the parameters causing varying EEG results in a structured manner, the analysis of the Annex 57 case studies is based on the EN 15978 standard and the assessment process defined therein (further specified in Table 2 of section 3.3). In contrast to the more general LCA guidance of the ISO 14040-14044 and the ISO 21931-1, the EN 15978 focuses on a specific approach to set up a study and calculate the potential impacts. In this sense, the standard reflects the assessor's practice and it covers the step-wise methodological choices that require attention in the assessment procedure [30]:

- Identify purpose of assessment
- Specification of the object of assessment
- Scenarios for the building life cycle
- Quantification of the building and its life cycle
- Selection of environmental data and other information
- Calculation of the environmental indicators

Additional, final process steps of the EN 15978 approach; "Reporting and communication" as well as "Verification" have been left out of this analysis as they do not specifically address the assessor's choices regarding methodological choices in the study.

3 Results and discussion

3.1 Reported EEG results from Annex 57 case studies

The EEG results of the Annex 57 case studies are displayed in this section in order to obtain an overview of the quantitative background results used for the analysis and discussion of methodological parameters. This background overview includes displaying the varying ranges in results as well as the numbered case studies which are later referred to in section 3.2 as part of the analysis. Table 1 presents a summary of the properties of the case study collection. Appendix A provides further details of the specific case studies and their individual properties in terms of country of origin, the building type, databases used for calculations, the reference study period, and the included life cycle stages of the assessment. Further qualitative details of the case studies are specified in the case study collection report [71]. In the following analyses, specific case studies are referred to by country and case study number, e.g. AT3.

Table 1. Summary of Annex 57 case study properties for case studies analysed in this paper

Total number of case studies	59
Study origin (country)	Austria (AT), Switzerland (CH), Germany (DE), Denmark (DK), Italy (IT), Japan (JP), South Korea (KR), Norway (NO), Sweden (SE), United Kingdom (UK)
Number of databases employed	19
Range in applied reference study period (RSP)	20-150
Number of applied system boundary combinations	18
Building types	Office, residential, school

Figure 2a-b presents the ranges of and average EE and EG of selected life cycle stages reported as part of the Annex 57 case study template. EE expresses the cases where results were explicitly reported as being non-renewable primary energy use, i.e. CEDnren. The numbers represent new construction as well as refurbishment projects, further detailed on case study level in Appendix A. Refurbishment cases report numbers for all, in the refurbishment, installed materials as part of the product life cycle stages (modules A1-A3 – refer Figure 1).

The numbers showcased in Figures 2a-b are specified for impacts within the same system boundaries (refer Figure 1) of either product stage (A1-A3), replacements during the use stage (B4) or selected EoL processes (C3+C4). As shown in Figures 2a-b, the ranges span profoundly, especially for the product stage EE and EG. Reported numbers of EG range between -7 and 1,100 kg CO_2-eq/m^2 and reported numbers of EE range between 943 and 12,000 MJ/m^2. Note here, that the negative EG-result (-7 kg CO2-eq/m2) reflect methodological implications of the inclusion of temporal carbon storage in wood. This is further discussed in section 3.2.5.

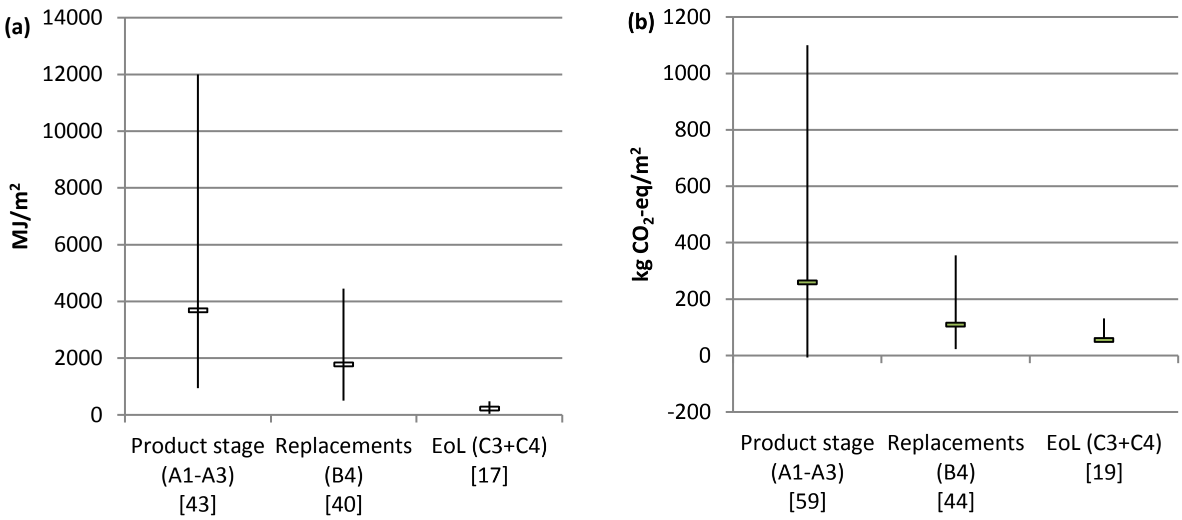

Figure 2. EE (a) and EG (b) averages and ranges from selected reported life cycle stages. Square brackets indicate number of case studies included in the displayed ranges

When adjusting results for the reference study periods used, the 41 case studies reporting product and replacement stages range the total EG between 0.3 and 18.2 kg CO_2-eq/m^2/year, i.e. a 60-fold difference. The 40 case studies reporting product and replacement stages for EE, show a range in the embodied impact of these life cycle stages between 16 and 210 MJ/m^2/year, i.e. an almost 15-fold difference.

Figure 3 displays EE and EG of the product life cycle stages, modules A1-A3, for each case study building (refer Figure 1). Results are ordered by increasing EE and the corresponding EG, although EG results reported without EE are also displayed in the right-hand side of the graph. Figure 3 shows how an increase in EE seems to be followed by an increase in EG. A linear correlation analysis between the two variables EG and EE yields an R^2-value of 0.70 signifying that there is a relationship between the two indicators. However, the relationship is not straight-forward because it reflects the multitude of underlying methodological parameters across the studies.

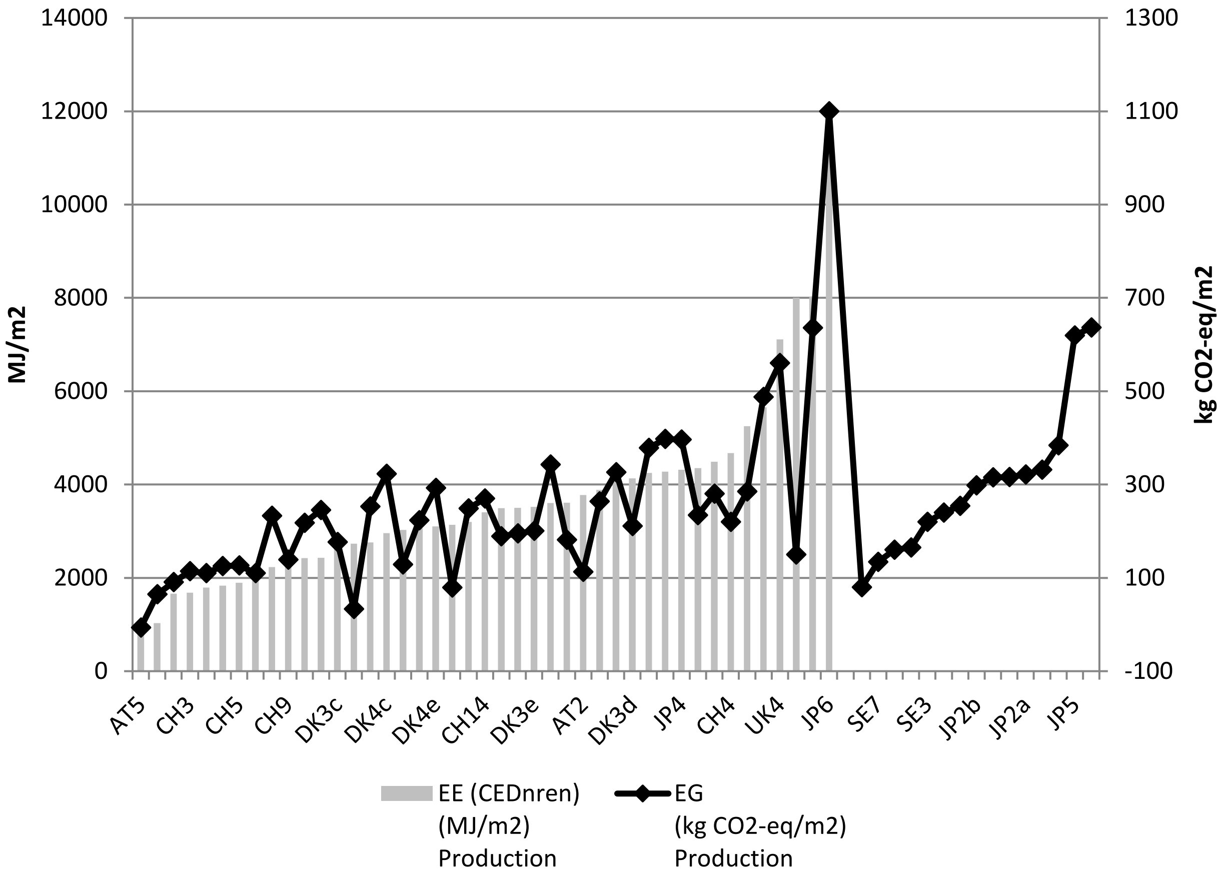

Figure 3. EE and EG of product stage (module A1-A3) of the Annex 57 building case studies

The differences in EEG results can further be specified according to some of the reported characteristics of each study. Figure 4a shows the EG results from the production stage (A1-A3) sorted by building use and 4b shows the EG results sorted by five of the applied databases.

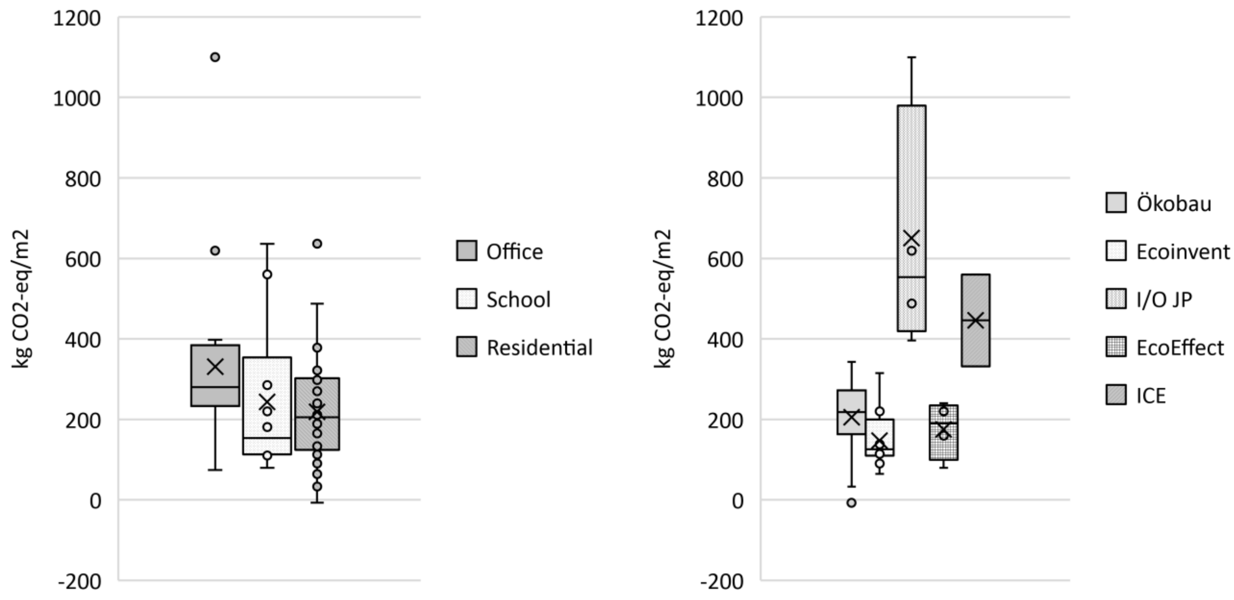

Figure 4a-b. Boxplots illustrating the distribution of EEG results from cases based on reported characteristics for building use type (4a) and database applied (4b)

Figure 4a-b shows two ways of categorising the results due to study characteristics. The figure also highlights how some characteristics are more influent than other, in this example it shows that results grouped by building use type reveals a variation in results although when grouped by database the variations become even more apparent. Each of the two characterisation types are only indicators of the specific case parameters affected; for the use type, this includes differences in building layout and material inventory etc. For the database type, this includes differences in GWP definitions, representativeness of data etc.

3.2 Significant methodological parameters of Annex 57 studies

In the following, the Annex 57 case studies are analysed and discussed within the framework of the assessment process steps outlined in section 2.2.

3.2.1 Identification of the purpose of assessment

The Annex 57 case studies present a range of different purposes for the individual studies. Examples include evaluations of early stage design decisions (SE2a, SE2b and SE5), assessments for different certification or benchmarking purposes (AT studies, DK4, CH studies), comparison of design options (UK5) and profiling for comparison with operational impacts (NO studies). The purpose of assessment, consisting of a defined goal and stated intended use, is the first step of an LCA study according to the international ISO 14040-series as well as the EN 15978 standards. These different stated purposes hence lead to variations in the subsequent methodological choices about functional unit, scope and other parameters made in each study. Standardisation is suggested as a general approach to limiting the uncertainties caused by choices in an LCA study [74]. However, as exemplified in the Annex 57 case study collection, the stated purposes of the building EEG assessments vary broadly and cause a wide range of diversity in the reported studies and results. Hence, a methodological one-solution-fits-all seems possible only on a theoretical scale although a highly detailed level of standardisation may be appropriate within certain contexts of purpose, e.g. for national certification, regulatory purposes or building-level EPDs.

3.2.2 Specification of the object of assessment

The Annex 57 case studies reflect a variation of different building types spanning various sorts of offices, residential single- or multi-family houses, schools and retirement homes. Even though the building type may point to some functional requirements of the building, this does not give any indications about the choice of building designs (e.g. high-rise concrete structure or single-storey wooden construction) nor the technical properties (e.g. thermal performance) that are relevant for embodied as well as operational impacts. Technical requirements such as thermal performance of the building is directly connected with not only operational impacts but also embodied impacts caused by material use in order to attain the required performance. However, reported performances such as “low-operational energy building” or “zero-emission building” as seen in the case studies, may still be perceived differently on an international scale due to differences in definitions and due to the different climatic conditions under which the buildings operate. The multitude of descriptions in the Annex 57 case studies of functional equivalents and physical characteristics of buildings points to the challenges in describing core functional and technical requirements as well as physical properties in a uniform and consistent way and thus complicates the possibilities of comparing studies horizontally.

An additional aspect of the functional equivalent is the reporting of results per m^2 floor area, a declared unit often used in conjunction with the functional equivalent. Even though individual studies may specify whether usable floor area or gross floor area is the reference unit, these terms may cover slightly different definitions from country to country. For instance, the heated floor area is in Norway measured to the inside of the external walls but in Denmark this is measured to the outside of the external walls [75]. Furthermore, national practices may vary as for how to include m^2 from parts of the building that are non-conditioned, e.g. basement or terraces.

The reference study period (RSP) is an important factor for the calculation and reporting of EEG results due to the relative significance of the recurrent embodied impacts. In the Annex 57 case studies, the reported RSPs range from 20-150 years and thus present very different perspectives on the temporal aspect of the assessment. The choice of RSP can be viewed from two perspectives; firstly as a numerical exercise for calculating annualised impacts, an often preferred way to report results of a building LCA. Reported annualised performance of a building can thus be much misleading depending on the context, for instance if only the cradle to gate EEGs are included in the assessment. The second perspective of the RSP is as a parameter reflecting the actual design, where solutions for extension or limitation of the building's service life are sought after. This latter perspective is employed in some Annex 57 case studies displaying examples of embodied impacts from increasing earth quake resistance performance to obtain an increased service life of building (JP4, JP6) or by adapting the building design to protect weaker components, such as windows, in order to increase the service life of these (DK3a-b).

As already thoroughly explored in literature, the significance of system boundary definitions to the EEG results cannot be understated. Standards and scientific recommendations suggests full inclusion of all life cycle stage processes, or transparency and clear descriptions about potential system boundary simplifications (such as cradle to gate) [30][13]. However, the Annex 57 case studies show how EEG assessments in practice operate with selections of process modules across life cycle stages. Only in few examples do the case studies follow the recommended system boundary types such as cradle to gate (SE studies) or cradle to site (NO4). The reasons for this disparity between recommendations/standards and practice may on the one hand be explained by the relatively recent harmonisation of approach. On the other hand the disparity may also reflect how the defined goal and intended use of the studies vary from study to study. In this sense, the varying system boundary definitions may each suit their specific purpose and hence question the very usefulness of a general harmonisation of EEG studies.

3.2.3 Scenarios for the building life cycle

Scenario definitions and the influence on the EEG results are explored from different angles in some of the Annex 57 case studies, sometimes as part of the goal and other times as part of sensitivity analyses. Case study (JP7) thus explores different scenarios for the EoL treatment of a wooden house as part of the goal of the study. Case study (DK1) is an example of a case study evaluating the scenario of the building's service life as part of sensitivity analyses.

The relatively long service life of a building implies special attention towards the use stage scenarios that are relevant to the EEG, in particular the scenarios that describe how materials, components or the building itself is maintained, repaired, replaced and refurbished. The underlying factors determining the impact on EEG results of these scenarios can be narrowed down to the *scale* of intervention and the *frequency* of intervention. Replacement of building materials is the most frequently included use stage process in the Annex 57 studies. A detailed account on the actual assumptions and scenarios for all replaced materials is not present in any of the case studies, which is to be expected due to the large amount of documentation work this would require. Some studies refer to national guidelines on the replacement frequencies (e.g. DK, DE and AT studies). However even within one country, assessment practice may be influenced by various sources for material service life definitions, e.g. by scientific research centres and specific product manufacturers, thus resulting in significant variations of scenarios applied for comparable buildings and modelling [72].

Other relevant scenario choices highlighted in some Annex 57 case studies relate to the EoL processes assumed to take place after the building's end service life. For specific constructions, some EoL processes and benefits from next product system may prove to significantly influence EEG results, e.g. in a wooden structured high-rise building (UK9) evaluating the effect of using a scenario of direct reuse of the wood (assumed the standard scenario) or a scenario of incineration without heat recovery.

3.2.4 Quantification of the building and its life cycle

The quantification of the building and its life cycle is, in the assessment practice showcased by the Annex 57 case studies, a matter of inventory level of detail and source of data. The access to a high level of detail for the specific building is based on knowledge that is progressively developed alongside the development of the building project itself. How this higher or lower level of detail may affect the EEG results can be evaluated in some of the Annex 57 case studies where the as-build highly detailed inventory (NO4) contributes to EG results that are notably higher than a comparable building case calculated at the very preliminary design stages (NO1)[72]. The early design stage evaluations may prompt relevant inventory simplifications and cut-off practices and hence result in lower calculated EG results as exemplified in some cradle to gate and early design stage evaluations (see SE2b, SE4).

3.2.5 Selection of environmental data and other information

The differences between and the need for harmonisation of methodology in EEG database sources are thoroughly discussed in scientific literature. Thus, within each building material database lies a range of inherent methodological choices, e.g. of data representativeness and system boundaries. The Annex 57 case studies report the usage of 19 different databases. Furthermore, 30 % of the case studies report using two or more different data sources in the assessments. The choice of database for an assessment may rely on factors such as availability or apparent geographical representativeness without further considerations on other specific details of importance to the calculated EEG results, e.g. whether the database considers carbon storage in wood products. However, this exact modelling detail of carbon storage seem imperative to the relatively low cradle to gate EG results reported in some studies (AT2, AT5, DK3b, DE2, DE4). When not balanced properly by EoL processes' release of the stored CO_2, the results of a cradle to gate assessment can turn negative (AT5) or simply just generate EG results in the lower range (e.g. DK, DE and

AT studies) compared with studies using other databases. Hence, when these EG numbers are used outside context, in simplified system boundaries representations, and without sufficient background explanations they may result in misinterpretations and misuse.

An additional overall choice regarding input data concerns the use of generic data or the use of product-specific data in the form of EPDs. The choice of one or the other option may again reflect at which point of the design stage the assessment is carried out. At early stage design, for instance, the exact knowledge of the products that are going to be used in the building does not exist and thus generic data is needed for LCA modelling. However, even for assessments carried out at later stages of the building design where the specific products are indeed known, it may prove difficult to locate product specific EPDs for all materials in the building. Hence, generic data or data from other databases is, in the assessment practice, used to fill in the data gaps, creating uncertainty as to whether system boundaries etc. are consistent in the different data [75].

3.2.6 Calculation of the environmental indicators

The specifics of the calculation of environmental indicators also lie as inherent choices in the Annex 57 case studies through the use of specific databases. Of the 19 databases used in the Annex 57 case study collection, one is input-output based (refer JP studies) and the rest are process based. This modelling approach in the Japanese case studies thus partly explains the studies being in the higher range of the reported EEG results.

Although the impact assessment scope of EEG studies focuses on primary energy use and GHG emissions as indicators, the exact definitions of these indicators can be ambiguous and/or missing documentation, as mentioned in section 1.2.2. The reporting template of The Annex 57 case studies was not detailed enough to convey this level of detail for the databases, and not even the background information for the case studies report the definitions. This in turn could be the consequence of the lack of harmonisation of indicators as mentioned by Frischknecht et al. [41].

3.3 Points of attention in the use of EEG results

A range of significant, methodological parameters in the assessment practice are presented in the previous sections 1.3 and 3.2 and summed up in Table 2. It is a deliberate choice from the authors of this paper not to address the exact numerical influence on EEG results caused by the different parameters, but rather to identify the points of attention to keep in mind when using EEG studies from external and/or international sources. The deliberate lack of focus on exact numerical influence is based on the fact that the many different methodological parameters interact. Hence, the numerical expressions of significance to EEG results will be specific only to the study in question due to the uniqueness of the exact methodological parameters of study.

Table 2. Summary of the points of attention within assessment practice that leads to differences in EEG results.

Process steps according to EN 15978	Information required, based on EN 15978	Points of attention identified in international EEG literature and practice
Identification of the purpose of assessment	Goal	Goal and intended use of study affects subsequent methodological choices, e.g. about functional equivalent, system boundaries etc.
	Intended use	
Specification of the object of assessment	Functional equivalent	Lack of international definitions and terminology to describe functional and technical requirements (e.g. zero-emission-building) as well as referencing units (definitions of m2)
	Reference study period	Reference study period set: - arbitrarily (as a numerical exercise to report annualised EEG results) - as the required service life of building (although no consensus exists on how to determine this)
	System boundaries	Variations in system boundaries at different levels: - selection of included building life cycle stages - selection of building model scope
	Description of the physical characteristics of the building	Uniqueness of building design and construction practice
Scenarios for the building life cycle	Description of scenarios for all periodic operations	Variations in available information on service life of materials and products Variations according to national practice, guideline and/or regulation, for instance: - waste management - building site regulations
	Description of scenarios for all included life cycle stages	
Quantification of the building and its life cycle	Quantification of all net and gross amounts of materials and products in the building's life cycle	Potential simplifications of the building scale LCI
	Type of LCI data	Variations in sources and their level of detail (drawings, BIM data etc.)
Selection of environmental data and other information	Environmental data used for calculations	Representativeness of data Generic or product specific data System boundaries of database(s): - including/excluding carbon storage in biomaterials - width of included input and output substances and resources in data's modelling background
Calculation of the environmental indicators	Choice of indicators and characterisation factors	CED definition: - primary or end-use energy - including/excluding feedstock energy - primary energy based on upper or lower heating value of chemical energy sources - point of measurement for renewable energy sources - primary energy content from uranium based energy GWP definition: - included GHG emissions - characterisation factors used for GHG other than CO2 - temporal scope of GHG emissions
	Calculation method for total life cycle impacts	Input-output, hybrid or process based modelling approach of data

The identified significant parameters of methodological importance summed up in Table 2 are key elements in order to use, interpret and transfer existing knowledge about EEG profiles and design strategies in buildings. Research have in several cases advocated for increased transparency in studies of embodied impacts [13]. With the points of attention described in Table 2, this paper now provides a structured overview of the methodological choices that is seen to influence EEG results and hence need additional focus in terms of transparent descriptions.

4 Conclusions and recommendations

In this paper, we systematically explain and analyse the methodological implications on quantitative EEG results obtained in the Annex 57 case studies and we point to the areas of assessment practice where there is a need for clarification of the LCA methodological approaches applied in the building sector. The analysis of methodological parameters is structured by the assessment calculation method provided by the EN 15978 standard. The content of table 2 thus presents an analytical approach that follows the stepwise methodological choices that are actually made in the building EEG assessment practice. Each of the six assessment process steps involves one or more methodological choices relevant to the EEG results.

In spite of a thorough standardisation format, assessments in practice are carried out in a multitude of ways. As exemplified in the Annex 57 case study collection, the stated purposes of the building EEG assessments are one of the drivers leading to these differences in practice and results. There is nothing wrong in the differences as such, but it increases the risk of misinterpretations if EEG case studies are used for inspiration in design practice or even in regulation without taking into account the influence from specific methodological choices. This shows that a common standard cannot suit all purposes, although it provides general guidance of practice. For individual studies, existing standards serve well as foundational guidelines within which to explore the environmental significance of a building and its life cycle. However, a high degree of detailed standardisation is appropriate for some purposes where horizontal comparison with other studies is inherent, e.g. certification and in the development of building regulations. Based on EEG assessments in practice, it is thus recommended to develop standards or guidelines that target specific contexts of purpose, e.g. national certification or regulatory purposes. These could well be inspired by the recommendations developed by Annex 57 for uniform definitions and templates which improve the description of system boundaries, completeness of inventory and quality of data, and consequently, the transparency of embodied impact assessments.

The diversity of EEG study practice impairs the direct use of results for horizontal comparisons or as inspiration for low-EEG design solutions. The transparency of reported studies is instrumental using the experience gained and to transfer knowledge to other cases. Furthermore, the transparency needs to apply to the specific areas of the study that are sensitive in terms of affecting the generated results. In this study, the methodological parameters which influence to EEG have been systematically addressed and are listed as points of attention in Table 2. For EEG study practitioners, it is recommended to address these points so as to ensure the correct understanding and use of a particular case study by a third party. For design practitioners seeking inspiration for low-EEG building design, it is recommended to evaluate existing, inspirational studies in light of the points of attention in Table 2 that clarify the choices that may affect results in a different methodological context. The combination potentials between these many methodological parameters signifies a multitude of ways in which the outcome of EEG studies are affected. Further research is needed to determine the quantitative significance of each of the methodological parameters listed in this paper. In light of the increasing efforts of regulation bodies and the building sector towards reducing EEG from buildings, awareness of these significant parameters is crucial in order to interpret and transfer existing knowledge about EEG profiles of and design strategies for buildings. The EEG resultsand identified methodological parameters presented in this paper will support the informed uptake of EEG and life cycle considerations in the building and construction sector and lead to the development of EEG regulation.

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Appendix A

Case study	Database	RSP	Product stage			Construction process stage		Use stage					End-of-Life				Next product system	Main concept	Type
			Raw material supply	Transport to manufacturer	Manufacturing	Transport to building site	Installation into building	Use	Maintenance	Repair	Replacement	Refurbished	Deconstruction	Transport to EoL	Waste processing	Disposal	Reuse, recovery or recycling potential		
Austria																			
AT1	baubook eco2soft	100	x	x	x						x	x						New	Office
AT2	baubook eco2soft	100	x	x	x						x	x						New	Residential
AT3	baubook eco2soft	100	x	x	x						x	x						New	Office
AT4	EcoBat	60	x	x	x						x		x			x		Refurbished	Residential
AT5	Baubook eco2soft	100	x	x	x						x	x						New	Residential
AT6	Ökobau 2009	50	x	x	x						x				x	x		New	Office
Switzerland																			
CH1	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH2	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH3	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH4	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH5	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH6	EcoInvent 2.2	60	x	x	x						x				x	x		New	School
CH7	EcoInvent 2.2	60	x	x	x						x				x	x		New	School
CH8	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH9	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH10	EcoInvent 2.2	60	x	x	x						x				x	x		New	Residential
CH11	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH12	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH13	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH14	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential
CH15	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential
Germany																			
DE1	Ökobau 2011	50	x	x	x						x				x	x	x	New	School
DE2	Ökobau 2011	50	x	x	x						x				x	x	x	New	School
DE3	Ökobau 2011	50	x	x	x						x				x	x	x	New	Residential
DE4	Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
Denmark																			
DK1	PE int	50	x	x	x						x				x	x	x	New	Office
DK3a	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential
DK3b	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential

DK3c	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Residential
DK3d	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Residential
DK3e	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Residential
DK4a	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4b	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4c	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4d	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4e	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4f	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4g	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
Italy																			
IT2	EcoInvent	50	x	x	x				x		x		x	x	x	x	x	Refurbished	Residential
Japan																			
JP2a	(Not specified)	-	x	x	x													New	Residential
JP2b	(Not specified)	-	x	x	x													New	Residential
JP3	Various	60	x	x	x	x	x				x	x	x	x	x	x		New	Residential
JP4	IO table Japan	60/100	x	x	x													New	Office
JP5	IO table Japan	60	x	x	x	x	x	x		x	x	x	x					New	Office
JP6	IO table Japan	50/100	x	x	x	x												New	Office
JP7	IO table Japan	-	x	x	x	x	x				x	x	x	x				New	Office
South Korea																			
KR3	KOR LCI	50	x	x	x	x	x									x		New	Office
Norway																			
N01	EcoInvent	60	x	x	x						x							New	Residential
NO2	EcoInvent	60	x	x	x						x							New	Office
NO4	EPD	60	x	x	x	x												New	Residential
NO9	EcoInvent	60	x	x	x						x							New	Residential
Sweden																			
SE2a	EcoInvent, BECE	50	x	x	x													New	Residential
SE3	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential
SE4a	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential
SE4b	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential
SE5	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Office
SE6	EPD, Ökobau 2013, EcoInvent, KBOB	1									x							Refurbished	Office
SE7	IVL Miljödata, EPDs, EcoInvent, KBOB, ICE	50	x	x	x	x	x			x		x	x	x	x	x		New	Residential
United Kingdom																			

UK4	BATH ICE, ECEB	68	x	x	x	x	x			x	x	x	x	x	x	x		New	School
UK5	ICE, EcoInvent, USLCI	20	x	x	x	x	x											New	Residential

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